Hand-held Virtual Reality: A Feasibility Study

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ABSTRACT

Hand-held computing devices are ubiquitous and have become part of our lives these days. Moreover, hand-held devices are also increasingly being equipped with special sensors and non-traditional displays. As such, it raises the question of whether such a "small" and "reduced" device could serve as an effective virtual reality (VR) platform and provide sufficient immersion and presence, e.g. through multimodal interaction. In this paper, we address this question by comparing the perceived field of view (FOV) and level of immersion and presence among the users' of VR platforms, varied in the sizes of physical/software FOV and in styles of interaction. In particular, we consider a motion based interaction, a style of interaction uniquely suitable for the "hand-held" devices. Our experimental study has revealed that when a motion based interaction was used, the FOV perceived by the user for the small hand held device was significantly greater than (around 50%) the actual. Other displays using the button or mouse/keyboard interface did not exhibit such a phenomenon. In addition, the level of user felt presence was higher than even that from a large projection based VR platform. The paper demonstrates the distinct possibility of realizing reasonable virtual reality even with devices with a small visual field of view and limited processing power.

Categories and Subject Descriptors

H.5.2 [**Information Interfaces and Presentation**]: User Interfaces – *Evaluation/Methodology, Interaction Styles*

General Terms

Experimentation, Human Factors.

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Keywords

Virtual Reality, Hand-held Devices, Presence, Field of View, Task Performance, Immersion, Motion based Interface.

1. INTRODUCTION

Hand-held computers have recently experienced extreme growth in terms of their performance and capabilities. Hand-held games and contents are now commonplace. Hand-held computers refer to computers that are small and light enough to be held in one hand such as personal digital assistants (PDA), cell phones, ultra mobile computers, and some of the recent portable game consoles (GBA or PSP[1]). Today's hand-held computers are equipped with processors approaching 1GHz performance with graphics accelerating chips, sound/signal processing modules and a sleuth of sensors (e.g. camera, gyros, light sensors) and multimodal displays (e.g. vibrators, auto-stereoscopic display). We can now easily find kids or even adults, in the streets, seemingly immersed and enjoying the contents or services provided through such devices. From the point of view of traditional virtual reality (that has pursued the replication of rich sensory experience in the large-scale), it is somewhat odd that people can feel immersed in such "small" environments. However, such could be explained easily from the on-going debate about "form vs. content" about user felt presence [20]. The "content" proponent would say that this is one evidence that "mind-catching" contents (no matter how simplistic the interaction or the sensory stimulation is) is sufficient to induce presence or the feeling of immersion.

On the other hand, we are interested in knowing if it is possible or how, to make these ever-advancing hand-held devices more "multi-modal" so that the user experience and task performance can be further enriched and improved. In this paper, we address this issue by comparing the perceived field of view (FOV), the level of immersion and presence, task performance and usability among the users' of various VR platforms including the hand-held device. That is, the VR platforms were varied in their sizes of physical/software FOV and in styles of interaction.

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[1] GBA and PSP are registered trademarks of the Nintendo and SONY Corporations.

In this comparative study, we considered the use of a motion based interaction as the factor for the style of interaction. Motion based interaction (e.g. gesture, direct interaction) is already considered a desirable style of interaction for virtual reality systems [3]. This is because it involves many parts of our body (if not the whole) and leverages on one's sense of proprioception, improving the overall user felt presence and immersion (and even task performance) [14]. In the case of hand-held devices, the motion based interaction also becomes coupled with the visual display/head (a situation unique to the hand-held device) because the sensors and the displays are all physically integrated (and moving) together. Currently, interaction in the handheld devices is still mostly button and finger-based and naturally, one way to enrich the user experience is to provide the body-based and motion based interaction. To realize motion based interaction (and to carry out the experiment), we have implemented relative tracking using a camera/accelerometer mounted on the hand-held device. Note that our notion of hand-held VR also hinges on self containment, without any external computational assistance.

The rest of the paper is organized as follows. The next section reviews some of the related work in hand-held virtual reality. Then we describe our experimental study in detail, including the implementation of the camera/accelerometer based tracking. Then, we report on the findings and give an analysis and conclusion on the possibility of realizing virtual reality with small-scale hand-held devices.

2. RELATED WORK

Possibilities for virtual reality with hand-held devices (palmtop computers) were first investigated in 1993 by Fitzmaurice et al. [6]. In this paper, the authors suggested several principles for display and interface for palmtop computer VR. Due to the limited technology at the time, the prototype was demonstrated and tested with a wired 6-DOF sensor and the display generated by a workstation.

Hand-held devices (with visual display) were perhaps first used in the context of virtual reality as interaction devices. Watsen et al. have used a PDA to interact in the virtual environment, but the interaction was mostly button or touch screen based and no tracking was used nor necessary [24]. Kukimoto et al. also developed a similar PDA based interaction device for VR, but with a 6-DOF tracker attached to it. This way, they were able to demonstrate 3D interaction such as 3D drawing through the PDA (moving it and pressing the button) [10]. Various special sensors and displays like accelerometer, gyros, vibro-tactile motors and even haptics have been used to enhance hand-held oriented interactive experience [9][17].

In particular, researchers have long been interested in using the camera (or computer vision) as interfaces for computers, particularly for 3D interactions [7][8]. Generally robust tracking with as little environment constraints as possible is a hard problem, and much more so with hand-held devices which lack the needed computational power [13]. However, the computational power of the hand-held devices is ever-more increasing with respect to their physical size and cost. Ballagas et al. has demonstrated direct manipulation for large displays using camera phones [1]. Paelke et al. has presented a foot-based interaction for a soccer game on a mobile device using a camera [15]. Hand-held augmented reality is also a popular form of virtual reality on a hand-held device. For example, Wagner developed hand-held (PDA) augmented reality system and applied it to the Signpost project (e.g. smart space with augmentation for navigation and information browsing))[22][23].

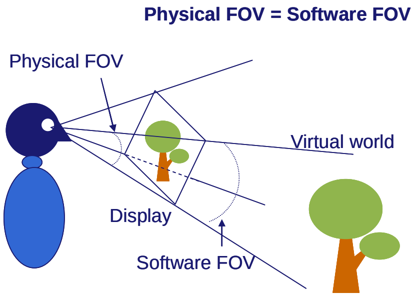
In our case, we use a SONY hand-held PC that is equipped with a 733 MHz Pentium processor, perhaps one of the most powerful hand-held computer, yet still short of that of the desktop computers. From our literature survey, we make a note that while there have been many novel implementations and attempts of applying hand-held devices to various aspects of VR, their utility has not been clearly shown or compared to the nominal VR systems in terms of presence, immersion and task performance.

3. EXPERIMENTS

The main purpose of this study was to assess the feasibility of virtual reality with relatively small screens (as in the hand-held devices) by taking advantage of other system factors, such as multimodal interaction, especially motion based interaction. The basic approach was to have the subjects navigate through a given virtual environment (Experiment I) and search and select objects (Experiment II) using VR platforms differing in their screen sizes and software (geometric) FOVs (SFOV). The software FOV (SFOV) differs from the actual physical FOV (PFOV) in that it refers to the angle encompassing a given scene in its original scale (See Figure 1). For instance, 100% SFOV coincides with that of the PFOV, and 200% SFOV would allow one to see twice as much angular-wise (or the scene is reduced by half angular-wise).

There were five conditions for the two experiments as shown in Table 1. The primary condition represents the motion based hand-held platform, and as comparison groups there were four others. The button-based hand-held platform represents the current form of the hand-held devices. To see the effects of "hand grasping" (whether the mere hand grasping contributes to a possible immersion or sustained attention), a small (same as the hand-helds) screen platform condition was also added. The desktop monitor and large PDP (Plasma Display Panel) display based platforms represent the nominal VR platforms with larger display sizes (larger PFOV and SFOV).

We performed two experiments. In Experiment I, the users were questioned for presence, system usability, enjoyment and perceived field of view after navigating through the virtual environment in the given platform. In Experiment II, the task (navigating and selecting objects) completion time was measured.



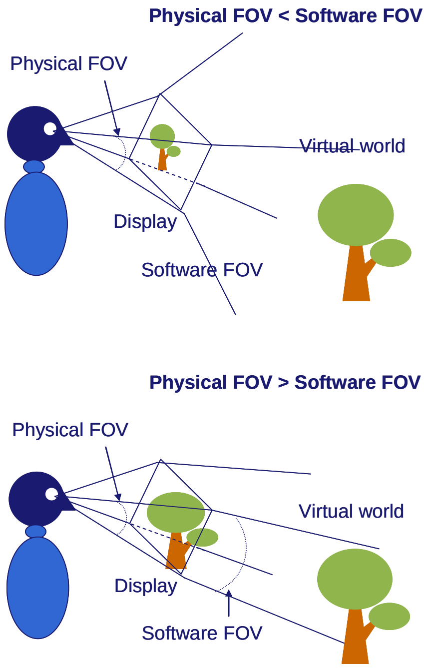


Figure 1. Relations between physical FOV and software FOV.

Table 1. Six test conditions in the experiment. Asterisks denote average values (when experimenting with the hand-held devices as it was not feasible to tightly fix the viewing distances)

Platform Characteristics Test Groups	Screen Size: width x height	Viewing Distance / Physical FOV	Software FOV
Hand-held / Motion based	10cm x 7.5cm	37.97cm* / 15°	30° (200%)
Hand-held / Button based	10cm x 7.5cm	37.97cm* / 15°	30° (200%)
Small Screen / Keyboard & Mouse	10cm x 7.5cm	37.97cm / 15°	30° (200%)
Desktop Monitor / Keyboard & Mouse	34cm x 26cm (17 in. diag.)	63.44cm / 30°	45° (150%)
Large PDP / Keyboard & Mouse	68cm x 51cm (42 in. diag.)	58.88cm / 60°	60° (100%)

3.1 Experimental Design and Procedure

A one factor within-subject experimental design was for both experiments. In both cases, the independent variable was the type of the VR platform. The major dependent variables for Experiment I were the level of presence/immersion, various usability, and perceived FOV, and for Experiment II, the task completion time. The subjects experienced each VR platform in an order specified by a balanced Latin-square design.

(a) Hand-held / Motion based

(b) Hand-held / Button based

(c) Small Screen / Keyboard & Mouse

(d) Desktop Monitor / Keyboard & Mouse

(e) Large PDP / Keyboard & Mouse

Figure 2. The five VR platforms tested.

For each experiment, the subject was first briefed for the main purpose of the experiment and one's vital information was collected such as age, gender, background, power of vision, color blindness, and experiences with 3D games or AR/VR systems. As the first experiment assessed presence and immersion, the respective subjects had to fill out an immersive tendency questionnaire which was adapted from the work by Witmer and Singer [25]. All subjects happened to fall in within the norm in terms of their immersive tendency (plus/minus twice the standard deviation) and thus, their data were all included in the final analysis. For a given VR platform, the subjects were given instructions as how to navigate or search and select the object. Few trials of training were given. For Experiment I, after completing the navigation task in the given VR platform, the subject was given a questionnaire to fill out about one's sense of immersion, presence, usability and perceived FOV. In Experiment II, the task completion time (search and select) was captured by the system automatically. While the experiments were designed as a one factor (i.e. VR platform) experiment, the results from the first two and last three test conditions (in Table 1) can be analyzed separately with respect to the factor of interface type and the sizes of the FOV respectively.

The overall experiment (for one subject) lasted about an hour. Figure 2 shows snapshots from the experiment. Twenty five subjects participated in each of the experiment. The subjects were engineering students (22 males and 3 females) with the average age of around 23, and paid for their services.

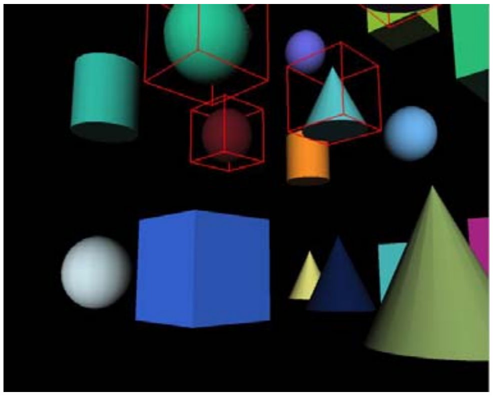
3.2 Experimental Tasks and Measurements

The experimental tasks carried out by the subjects in the two experiments were as follows. For Experiment I, at the start of the experiment, given a particular VR platform, the subject was situated in front of a virtual office building, and was asked to enter and navigate through the building for five minutes. The duration of five minutes was derived from a separate prior experiment to give a sufficient amount of time for the user to adapt oneself and establish one's spatial sense and orientation in the virtual environment [11]. Figure 3(a) shows the snapshot from the test environment for the navigation in Experiment I. Table 2 shows the presence/usability questionnaire used in Experiment I. The questionnaire was adapted from those of the standard usability surveys [3][4], Witmer and Singer [25] (which indirectly assesses presence by asking questions about various contributing factors to presence) and Slater and Usoh [21] (which directly asks about one's feeling about immersion and presence). The questions were answered in the 7-Likert scale. The final "presence score" was computed as the averaged value of answers of questions that were directly deemed related to presence. In Table 2, those questions are shown in bold face. This was more for the sake of simplicity, and an analysis with respect to answers to each individual question was surely possible.

As for assessing the perceived FOV, the questionnaire included a question of whether the display of the given VR platform provided sufficient FOV. In another assessment, the user was asked to mark on a pictorial snapshot of the virtual environment the extent to which one felt one could see through the display (See Figure 4).

For Experiment II, the subjects were situated in another environment, filled with geometric objects (such as spheres, cubes, cones, and cylinders) in 3D space. The subjects were asked to navigate, search and select a particular type of geometric object as fast as they could (Figure 3(b)).

(a) Navigation environment used in Experiment I



(b) Search and selection environment used in Experiment II

Figure 3. The two test virtual environments.

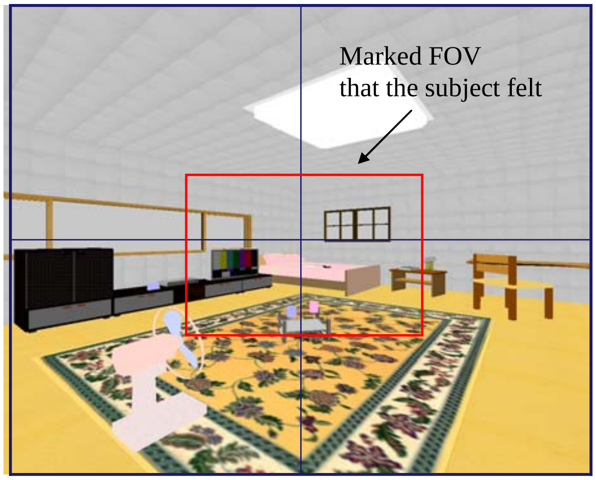


Figure 4. Measuring the perceived FOV. The subjects were asked to mark along the horizontal and vertical lines the extent one felt one was able to see through the display.

Table 2. Presence/Usability questionnaire

Category	Questions for each treatment
Visual	**How natural was the virtual environment?**
	How real was the virtual environment?
	Rate your depth perception.
	How large did you feel the "bird cage" was?
Auditory	**The sound effect helped me feel like I was in the environment.**
	Were you able to distinguish between different sounds?
	Were you able to tell where the sound was coming from?
Interface / Usability	The interface was easy to use.
	The interface was easy to learn.
	The interface was felt natural to use.
	The interface was intuitive.
Presence / Immersion	**Was the visual, auditory, and haptic stimulation felt consistent with one another?**
	How much disparate did you feel the virtual world was from the real?
	When carrying out the task did you think you were concentrated, focused or immersed?
	How much did you feel like looking at a real environment?
	How much were you involved in the environment?
	Did you feel like being in the environment?
Distraction	**How much were you distracted by the test environment?**
	Were you able to remember what environment objects were present?
Enjoyment	How much did you enjoy navigating through the environment?
Cyber-sickness	Did you feel sick navigating through the environment?
FOV	**Was the field of view sufficient for navigating through the environment?**

3.3 Experimental Setup (Interfaces)

As for the experimental set up, the different display sizes and SFOV used for each VR platforms are summarized in Table 1 and well illustrated in Figure 2. There were three types interfaces used for the various VR platforms for two tasks (navigation in Experiment I/II and selection in Experiment II). The three types of interfaces were (1) motion based (for the hand-held device), (2) button based (for the hand-held device) and (3) keyboard & mouse (for the rest). Table 3 summarizes the details of how they worked.

Table 3. The detailed description of the three interfaces used in the experiments

Interfaces	Task	Description
Motion based (Hand-held with two hands)	Navigation	Front/Back: Move front/back Rotate L/R: Rotate around Y Rotate U/D: Rotate around X
	Selection	Move close to object and press button (L. hand)
Button based (Hand-held with two hands)	Navigation	Front/Back: 2 buttons (L. hand) Rotate L/R: 2 buttons (R. hand) Rotate U/D: 2 buttons (R. hand)
	Selection	Move close to object and press button (L. hand)
Keyboard and Mouse (3 other non-hand-helds)	Navigation	Front/Back: 2 mouse buttons (R. hand) Rotate L/R: 2 arrow keys (L. hand) Rotate U/D: 2 arrow keys (L. hand)
	Selection	Move close to object and press mouse button (R. hand)

3.4 Implementation

To realize motion based interaction, it is necessary to track relative motion of the hand-held device. Relative tracking refers to an approximate tracking of the hand-held VR system (thus, the user's hand or body) in relation to the operating environment. Before moving on to the experimental results, we shortly explain how the relative motion tracking was implemented for the motion based interaction with the hand-held devices.

3.4.1 Relative Motion Tracking

To make our hand-held VR system as self-contained as possible, we integrated a vision based motion tracking and 3-axis accelerometer. Cameras (e.g. phone-cams) and accelerometers are becoming viable sensors for today's hand-held devices (e.g. Samsung SPH-S4000, SPH-S310). Our motion tracker tracks motion in 4 degrees of freedom, i.e. forward/backward movement, rotation about Y axis (yaw) and tilts about the X and Z axis (pitch, roll) (See Figure 5)[5]. The forward/backward motion and rotation around Y axis are estimated with the optical flow. We used the pyramidal implementation of the Lucas-Kanade feature tracker for matching the features between two sequential images [2][19]. The tilts about the X and Z axis were measured using a 3-axis accelerometer. The tilt data from the 3-axis accelerometer were digitized in relatively low resolution (8 bit, 0.92°~6.51°), and relying only on them resulted in an unstable virtual camera control. We filtered the data from accelerometer when the motion flow as recognized from the camera was not significant (within a given threshold).

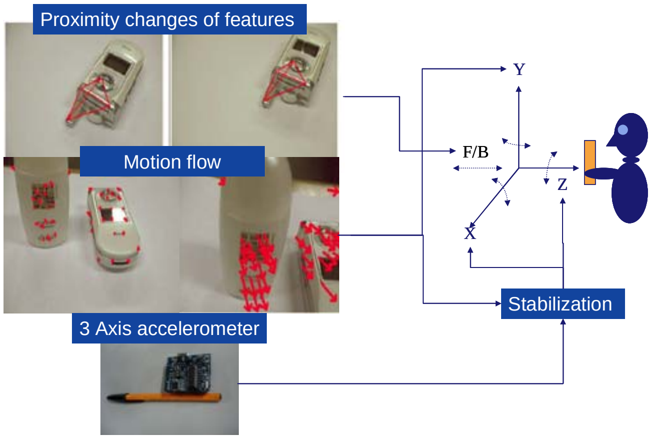


Figure 5. 4-DOF hand-held motion tracking with the camera and 3-axis accelerometer.

The particular choice of the degrees of freedom derives from our observation of the users. For instance, directing pure lateral translation in a hand-held posture is rather unnatural (e.g. left/right). It is more natural to rotate around the Y axis (perpendicular to the ground, around the body) to gain the similar effect. Similar argument goes for moving up and down. It is hard to imagine the user walking side ways (holding the hand-held device in the middle) or moving the hand-held device sideways away from the middle of the body to achieve pure "translation."

Even though the forward/backward and Y-axis rotation tracking is only approximate (mostly due to the use of single camera without marker in the environment, its resolution, etc.), the user is still able to interact quite naturally relying on one's hand-eye coordination and quickly adapting to the small inconsistency between the scale of the movement between the real and the virtual worlds.

3.4.2 Implementation Details

The hand-held PC model VGN-U71P from SONY was used for this study. This hand-held PC has the Intel Pentium M733 as its processor, 512MB of main memory and 5 inch LCD display and runs the desktop OS (WindowsXP). An ordinary USB camera (QuickCam series by Logitech) was used and OpenCV [27] and Coin3D [28] were used for image capture/processing and 3D graphics. MMA7260Q 3-axis accelerometer by Freescale, Inc. was used for detecting two axis tilts.

4. RESULTS

We used the ANOVA to verify the significance of conditions and the Student-Newman-Keuls test for grouping the test conditions with respect to the statistical results. We give a report to the major findings of our study with regards to the perceived FOV, presence, immersion, usability, task performance, enjoyment and cyber-sickness.

4.1 Perceived FOV and Presence (Collective)

There are many evidences that physical and software FOV has effects on the presence and immersion [12][16]. But with hand-held device, due to the relatively limited screen size, the SFOV is also limited. It is known that distortion in depth/size perception starts to occur with SFOV that is over twice that of the PFOV [26]. This limitation of FOV looks like impossible to overcome. But when we think about the human visual system, although the projected image onto the retina is limited in area and perceived in low resolutions outside of central parts, we still can perceive wider FOV with saccadic eye movements [18]. Inspired by this, we established the hypothesis that the perceived FOV could be widened with the motion based interaction. To verify this hypothesis, we assessed and measured the perceived FOV of the various VR platform conditions with the two methods as mentioned in Section 3.2, i.e. assessing the sufficiency of the FOV by score and marking on the pictorial snapshot of the virtual environment. Figure 6 shows the ANOVA results for the case when subjects marked the extent of their perceived FOV, and it suggests that the perceived FOV is significantly widened compared to the physical FOV ($F_{4,96} = 12.72$, $p < 0.0001$ in marking). The scoring method also produced a similar result with statistical significance ($F_{4,96} = 9.31$, $p < 0.0001$).

Also with Student-Newman-Keuls test, the perceived FOV in case of motion based interaction was grouped with desktop VR which provided 45° FOV. This means the motion based interaction widened perceived FOV (for the small hand-held device) over 50% of the actual FOV. The result that this effect does not appear in other conditions (e.g. button based hand-held or small screen) and we can easily conclude that the motion based interaction was the factor in causing this phenomenon.

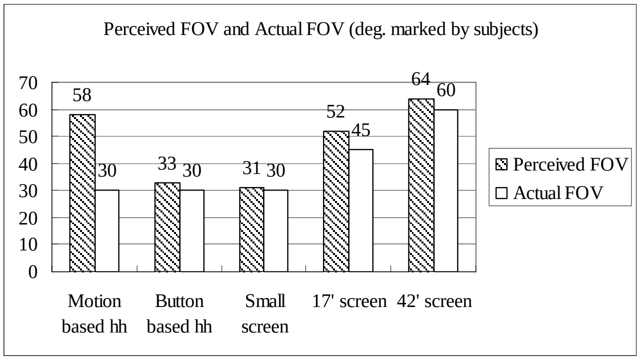


Figure 6. Perceived FOV (marked by subjects). Left is the perceived and the right is the actual.

In addition to the support by the existing literatures [12][16], the perceived FOV, in our study, also had a strong correlation with immersion and presence (Pearson correlation value was 0.301, $p = .001$ with immersion, correlation value was 0.475, $p < .0001$ with presence). Presence and immersion significantly improved with the motion based interaction (immersion: $F_{4,96} = 5.38$, $p = .0005$, presence: $F_{4,96} = 17.43$, $p < .0001$) (See Figure 7).

As already mentioned, the presence score was computed by averaging the answers to the presence-related questions with equal weights. This was done because there was no base for us to favor certain questions over others. Although not reported in detail here (for lack of space), the analysis with regards to the individual questions were consistent with the overall results.

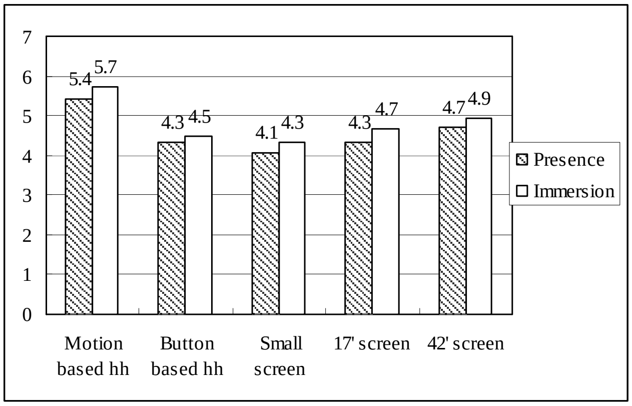


Figure 7. Immersion and presence score.

4.2 Usability and Task Performance

We assessed the usability of the systems in four categories: ease of use, ease of learning, naturalness, and intuitiveness (See Figure 8). The motion based hand-held platform came out to be easier to use than the button based hand-held and the small screen ($F_{4,96} = 3.30$, $p = .0168$), but not than others. No particular results were found in terms of learnability probably because all interfaces were sufficiently simple and easy to understand. The motion based hand-held platform was superior in naturalness and intuitiveness (naturalness: $F_{4,96} = 7.99$, $p < .0001$, intuitiveness: $F_{4,96} = 24.25$, $p < .0001$) than the other four groups (which were grouped together as one by the SNK test).

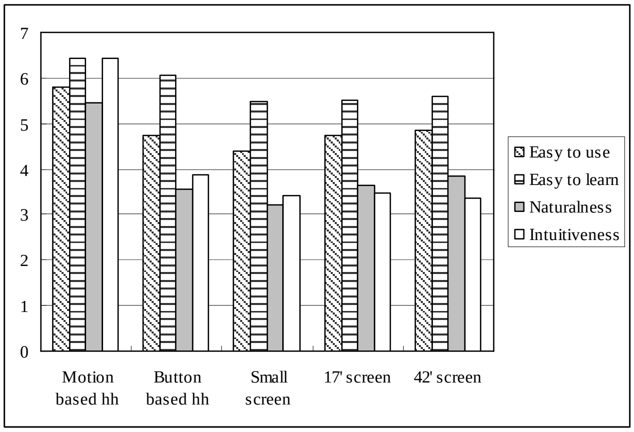


Figure 8. Results of usability tests: ease of use, ease of learning, naturalness, and intuitiveness.

Task completion time was the best (shortest) with the motion based interaction, and with other interfaces the task performances were similar ($F_{4,96} = 8.88$, $p < .0001$)(Figure 9).

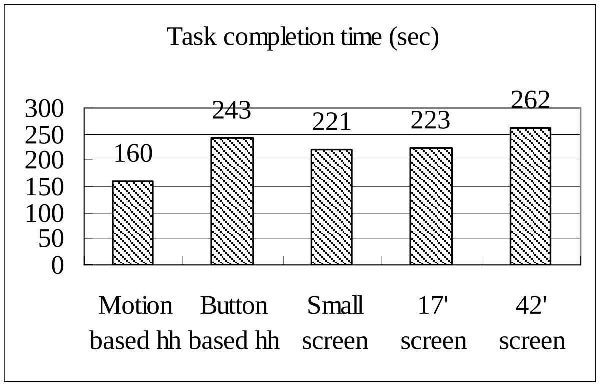


Figure 9. Task completion time (search and select).

4.3 Enjoyment and Cyber-sickness

Because entertainment is one of popular application areas for the hand-held platform, the enjoyment is another important goal for interface design of hand-held platforms. The level of enjoyment of motion based interaction was significantly better than other four ($F_{4,96}=7.58$, $p < .0001$). And the other 4 groups were not significantly different in their enjoyment level.

One of our concerns was the increase of the possible cyber-sickness with the motion based interface. While a bit of a tendency of cyber-sickness was observed the statistical results grouped all five groups equal in the level of cyber-sickness.

5. DISCUSSION AND CONCLUSION

This paper presented the procedure and results of a feasibility study for hand-held VR. The results have shown that the motion based interaction, a unique characteristic of hand-held platforms, can help improve the perceived FOV and presence/immersion up to a level comparable to the nominal VR platforms. The motion based interface also has shown promising results in terms of task performance leveraging on humans sense of proprioception. In the process of the study, a camera/accelerator based relative tracking technique has been developed to realize the motion based interaction on the hand-held device. We believe the widely perceived FOV is due to the similarity of the motion based interaction to the human visual system. This similarity was particularly effective because of the relatively small visual display. Also subjects experienced more enjoyment with motion based interaction without significant cybersickness.

With these results alone, it is plausible to conclude that hand-held VR is a distinct possibility and has good potential to provide sufficient immersion and presence (comparable to nominal VR systems) with other added factors such as multimodality (e.g. voice, tactile/haptic feedback, stereo display, etc), and environment binding/interaction (e.g. playing motion based golf on a grass field).

Our motion based interaction technique works reasonably well in static environment, but not so in a dynamic (e.g. in fast moving car with the camera faced outside) or plain (no corner features) environments, due to the nature of the approach. And the zooming factor is only approximate to that of the real world scale. We are continuing to improve the algorithm and would like to investigate how the inexact match between the amounts of movement between the real and virtual world affects the user perception. Moreover we are developing other multimodal displays for hand-held VR such as viewing-distance dependent display rendering and multiple vibro-tactile displays. Further validation is needed through exploration of various hand-held VR applications.

6. ACKNOWLEDGEMENTS

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